Higgs Boson Production with Heavy Quarks at Hadron Colliders

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Dissertation Defense

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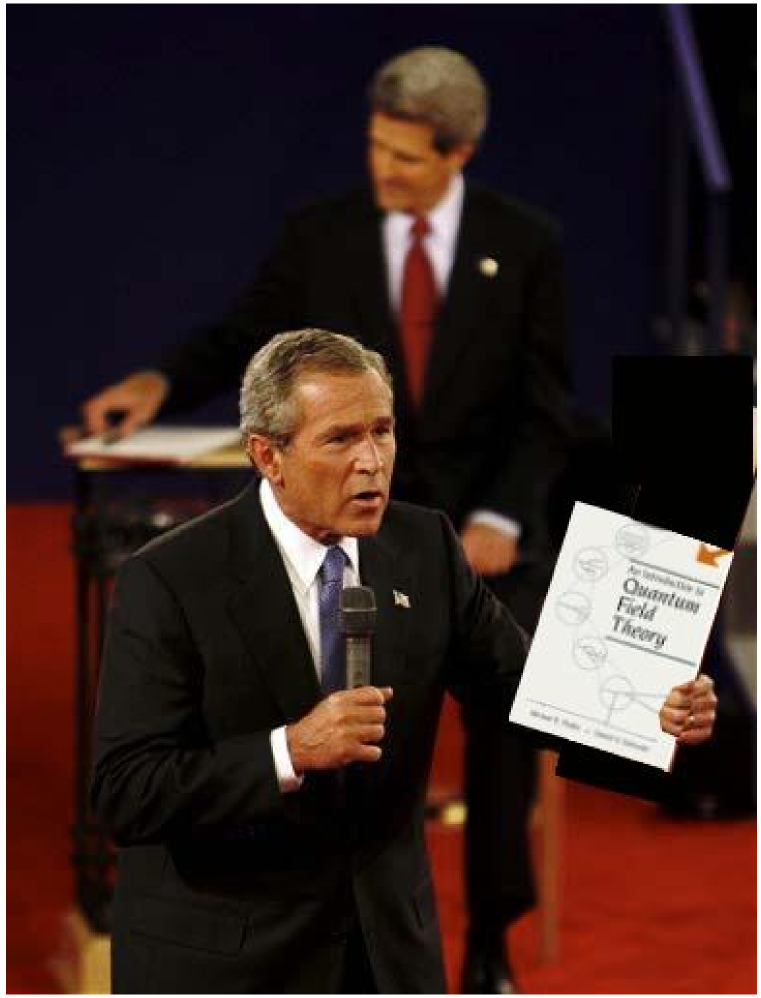
Outline

- SM Higgs sector
- MSSM Higgs sector
- Where's the Higgs?!? (Direct and indirect searches)
- Higgs Production with Top Quarks (at the LHC)
- Higgs Production with Bottom Quarks
  (in particular at the Tevatron)
- Summary

Higgs Physics in the U.K.

Radiative corrections is *hard work* !!!



The Standard Model

- Standard Model (SM): theoretical framework which best describes physics of elementary constituents of matter.
- It is a gauge theory based on the gauge group:

$$SU(2)_L \times U(1)_Y \times SU(3)_C$$

$$SU(2)_L \times U(1)_Y \longrightarrow \text{Electroweak Interactions} \longrightarrow W^{\pm}, Z^0, \gamma$$
$$SU(3)_C \longrightarrow \text{Strong Interactions} \longrightarrow \text{gluons}$$

- Explicit gauge boson mass terms forbidden by gauge symmetry
- What the...?!?

$$M_W = 80.426 \text{ GeV} \;\text{ and }\; M_Z = 91.188 \text{ GeV}$$

The Higgs Mechanism

- One way to introduce gauge boson masses is by spontaneously breaking (...or hiding) the EW symmetry via the Higgs mechanism:

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger (D^\mu \Phi) - [\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2] \equiv (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi)$$

- Higgs (complex) $SU(2)_L$ doublet (= four degrees of freedom):

$$\Phi = \begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ \phi_3(x) + i\phi_4(x) \end{pmatrix}$$

- Minimize the potential $V(\Phi)$...

$$\mu^2 > 0 \quad \longrightarrow \quad \Phi^\dagger \Phi = 0 \longrightarrow \text{niente di nuovo!}$$

$$\mu^2 < 0 \quad \longrightarrow \quad \Phi^\dagger \Phi = \frac{-\mu^2}{\lambda} \equiv v \longrightarrow \text{perfetto!}$$

The Higgs Mechanism (cont.)

- To ensure $SU(2)_L \times U(1)_Y \xrightarrow{\text{SSB}} U(1)_{em}$, we rewrite Φ to make the physical scalar degrees of freedom explicit via a gauge rotation:

$$\Phi(x) = \frac{e^{\frac{i}{v}\vec{\chi}(x)\cdot\vec{\tau}}}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \xrightarrow{SU(2)} \Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

- Three original d.o.f.'s $\rightarrow$ $M_{W^\pm}^2 = \frac{1}{4} g^2 v^2$ and $M_Z^2 = \frac{1}{4}(g^2 + g'^2)\, v^2$
- Fourth original d.o.f. $\rightarrow$ SM Higgs boson, h ($M_h = -2\mu^2 = 2\lambda v^2$)
- Bonus: interactions between the weak gauge bosons and the Higgs boson

$$g_{VVh} = 2i \frac{M_V^2}{v} g^{\mu\nu}$$

What about the Quarks?

- Introduced as spin $= 1/2$ fields and organized in multiplets carrying the quantum numbers of the gauge group:

$$Q_L^i = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L , u_R^i \text{ and } d_R^i$$

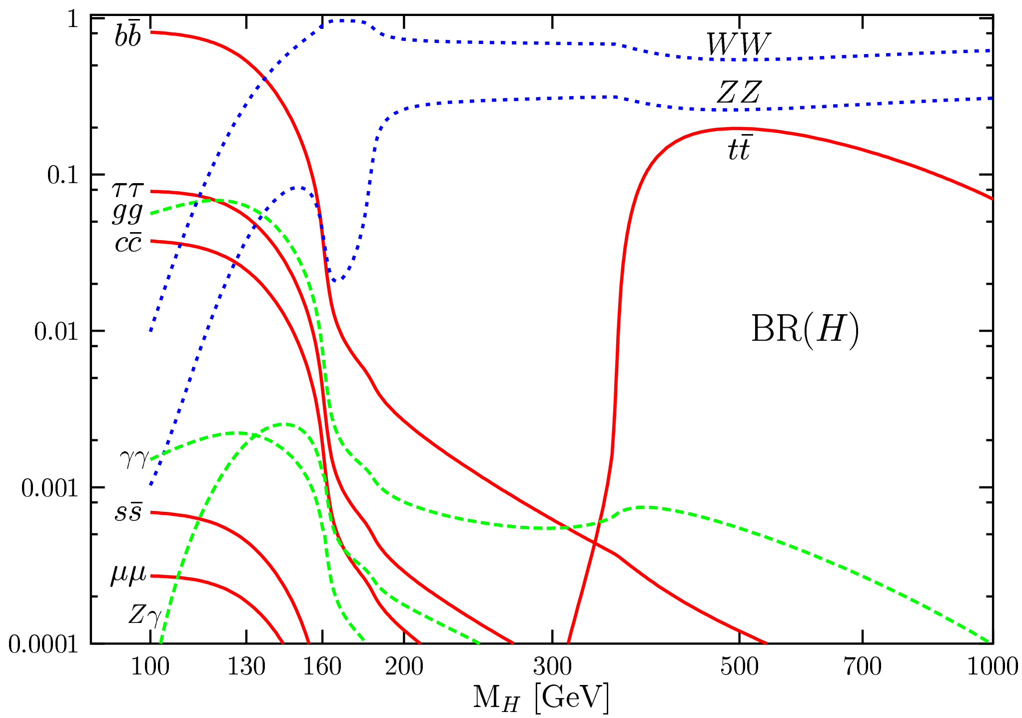
- Gauge symmetry forbids explicit mass terms...but, adding Yukawa interactions:

$$\mathcal{L}_{Yukawa} = -\Gamma_u^{ij} \bar{Q}_L^i \Phi^c u_R^j - \Gamma_d^{ij} \bar{Q}_L^i \Phi d_R^j + h.c.$$

- When Φ acquires vev, SSB communicated to fermionic sector:

$$m_q = \Gamma_q \frac{v}{\sqrt{2}} \quad \text{and} \quad g_{q\bar{q}h} = \frac{\Gamma_q}{\sqrt{2}} = \frac{m_q}{v}$$

SM Higgs Boson Decays



- Below WW threshold (light Higgs), $h \to b\bar{b}, \tau^+\tau^-, \ldots, \gamma\gamma$
- Above WW threshold (heavy Higgs), $h \to W^+W^-, ZZ, t\bar{t}$

However...

- "Theoretical concerns":
  - 'Ad hoc-ness': Higgs scalar doublet added *by hand*
  - Arbitrariness: Higgs mass and the Yukawa couplings are undetermined
  - Why/how $\mu^2 < 0$?
  - Extreme fine-tuning: calculation of M_h depends quadratically on Λ

$$M_h^2 = (M_{h,0})^2 + k\,\frac{g^2}{16\pi^2}\,\Lambda^2$$

- "Theoretical solution": Supersymmetry predicts solutions to a few of these issues (~~see~~ ...buy Howie's book)

MSSM Higgs Sector

- Two Higgs Doublets:

$$\Phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix} \ , \ \Phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_u^- \end{pmatrix}$$

- Same principle, but more complex Higgs potential. Minimum occurs for:

$$\langle \Phi_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \qquad \langle \Phi_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix}$$

- Can choose v_u and v_d such that: $v^2 = v_u^2 + v_d^2$.
- After SSB, five scalar d.o.f.'s left over $\rightarrow h^0, H^0, A^0, H^{\pm}$

MSSM Higgs Sector (cont.)

- Due to SUSY constraints on Higgs potential, MSSM Higgs sector fully described by two parameters: $\tan\beta \equiv \frac{v_u}{v_d}$ and M_A, s.t.

$$M^2_{H^0,h^0} = \frac{1}{2}\left(M^2_{A^0} + M^2_Z \pm \sqrt{(M^2_{A^0}+M^2_Z)^2 - 4M^2_Z M^2_{A^0}\cos^2 2\beta}\right)$$

$$\Downarrow$$

$$M_{h^0} < M_Z \xrightarrow{SUSY} M^{max}_{h^0} \simeq 130 \text{ GeV}$$

- Hierarchy of Yukawa couplings can be quite different:

$$h^0(H^0)b\bar{b} \quad : \quad \frac{-\sin\alpha(\cos\alpha)}{\cos\beta}\, g^{SM}_{b\bar{b}h}$$

$$A^0 b\bar{b}(t\bar{t}) \quad : \quad \gamma_5 \tan\beta\, g^{SM}_{b\bar{b}h}(\cot\beta g^{SM}_{t\bar{t}h})$$

$$h^0(H^0)t\bar{t} \quad : \quad \frac{\cos\alpha(\sin\alpha)}{\sin\beta}\, g^{SM}_{t\bar{t}h}$$

Where is (are) the Higgs boson(s)?!?

- Direct search performed at CERN's LEP2 using $e^+e^- \to Zh$ $(h = h^{SM}, h^0, H^0)$ and $e^+e^- \to h^0 A^0$:

$$
\begin{aligned}
M_{h^{SM}} &> 114.4 \text{ GeV } (95\% \text{ C.L.}) \\
M_{h^0,H^0} &> 91.0 \text{ GeV } (95\% \text{ C.L.}) \\
M_A &> 91.9 \text{ GeV } (95\% \text{ C.L.})
\end{aligned}
$$

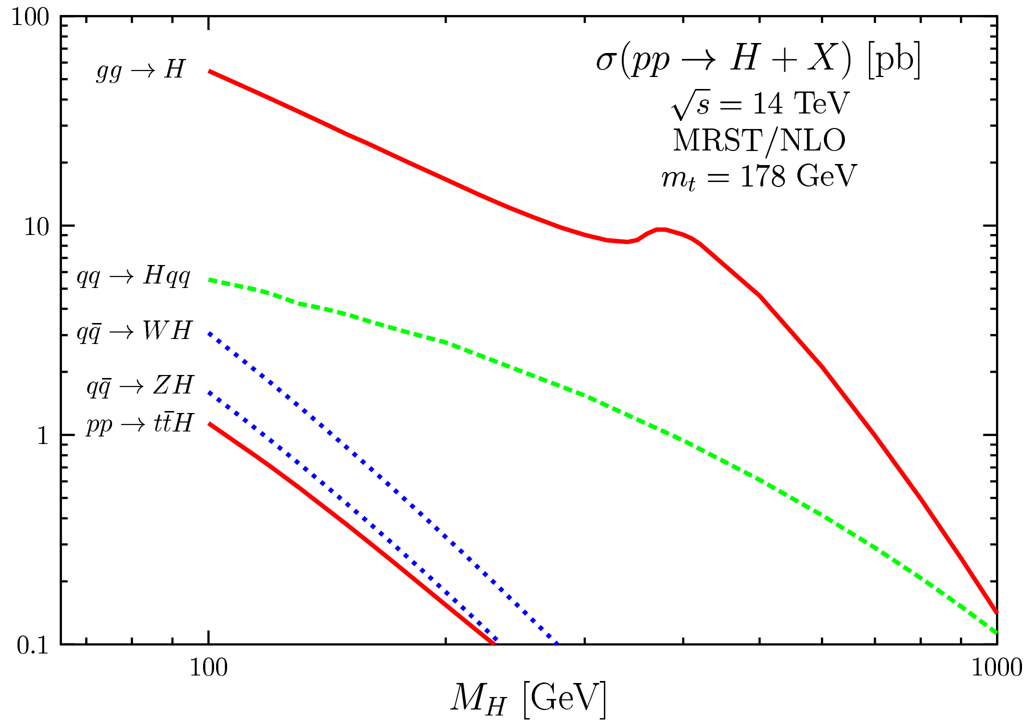
- Precision Electroweak Measurements (e.g. M_W, M_Z, etc):

$$
\begin{aligned}
M_{h^{SM}} &= 129^{+74}_{-49} \text{ GeV (best fit)} \\
M_{h^{SM}} &< 285 \text{ GeV } (95\% \text{ C.L.})
\end{aligned}
$$

- Theoretical Constraints (e.g., if SM survives all the way to M_{Pl}):

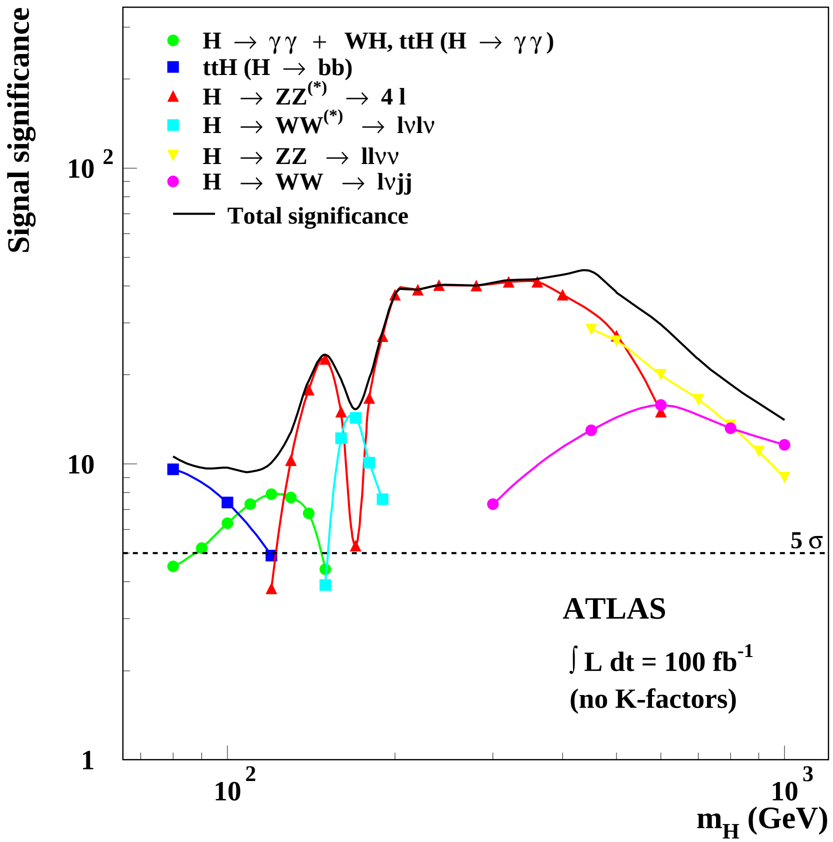
$$130 \text{ GeV} < M_h < 180 \text{ GeV}$$

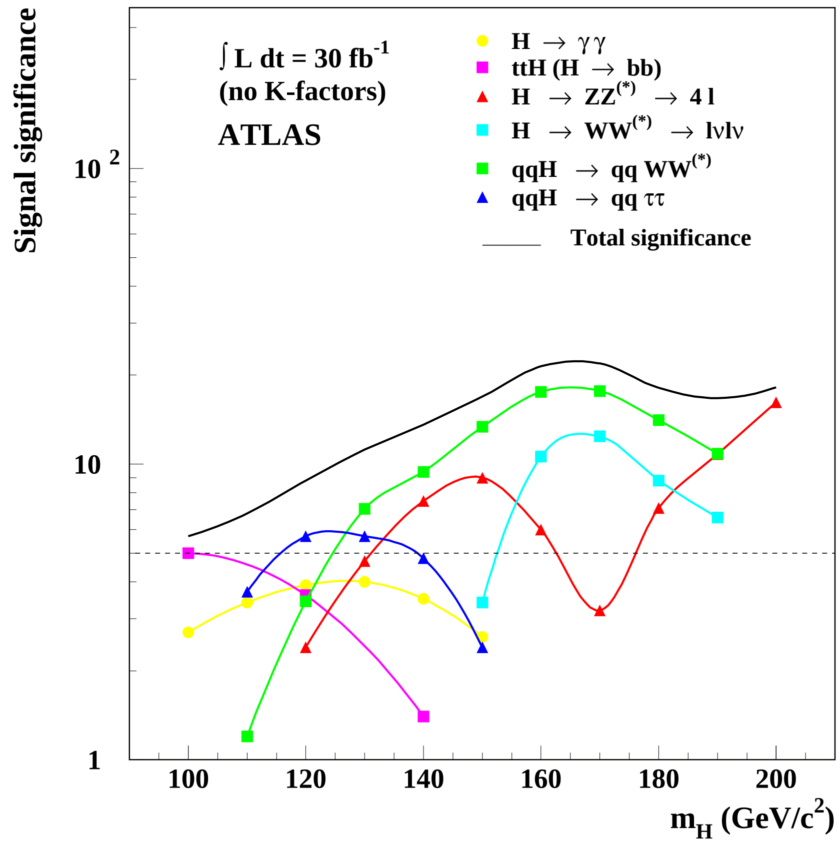
SM Higgs Production at the LHC



- For light Higgs bosons: $h \to b\bar{b}$ and dominant channels are hindered by huge hadronic backgrounds
- Search for subleading process followed by $h \to b\bar{b}$ in low M_h range

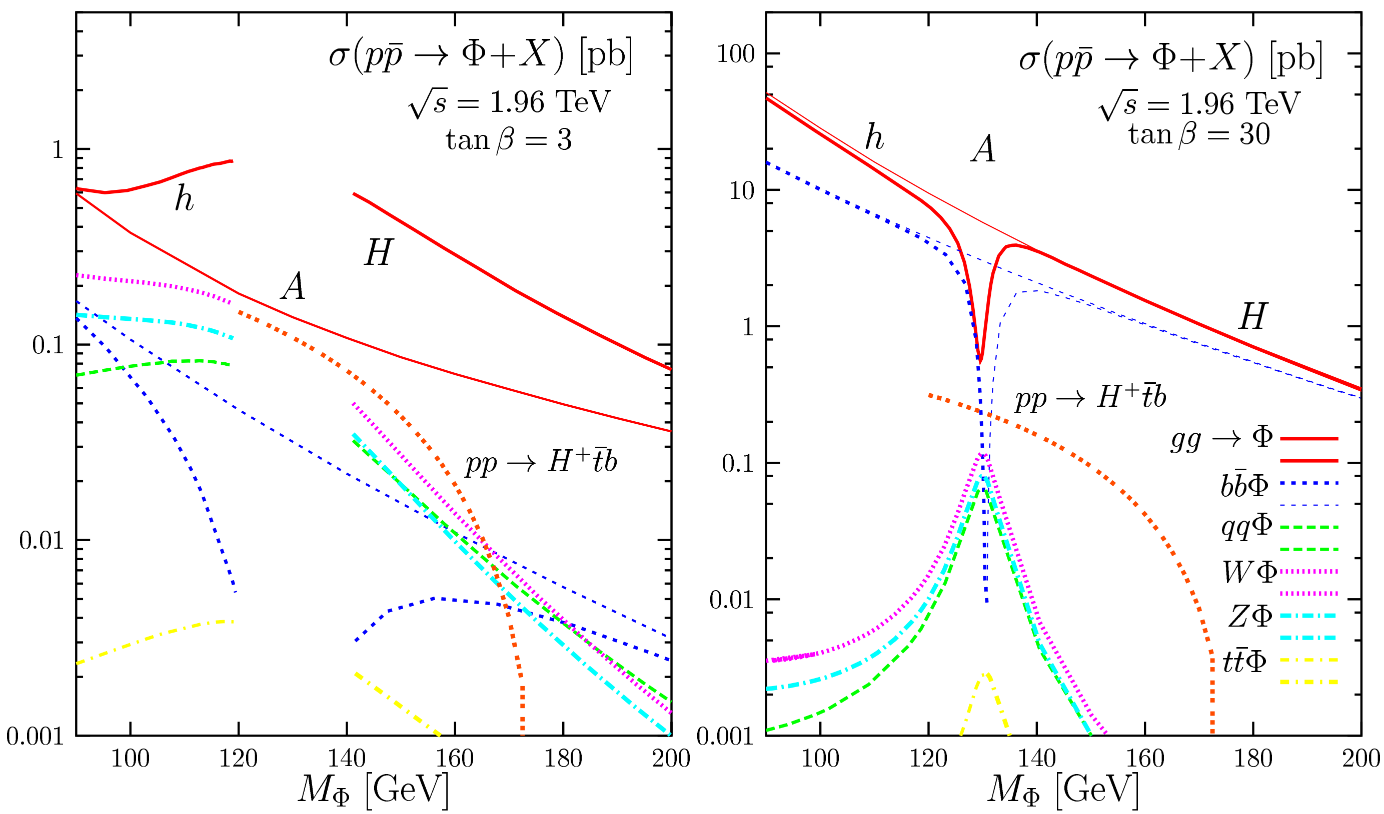
Discovery at the LHC





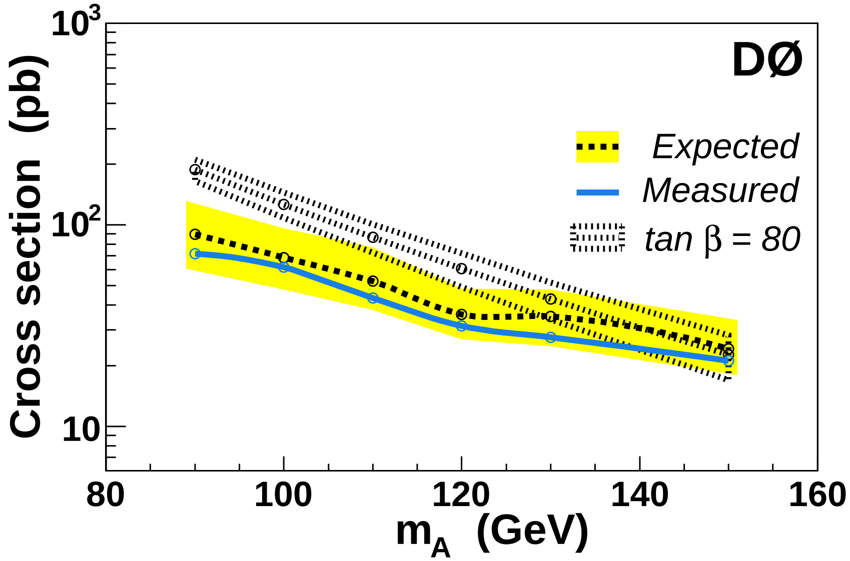
- For light Higgs ($M_h \simeq 115 - 140$ GeV), $t\bar{t}h$ crucial for discovery
- Only unambiguous measurement of $g_{t\bar{t}h}$!

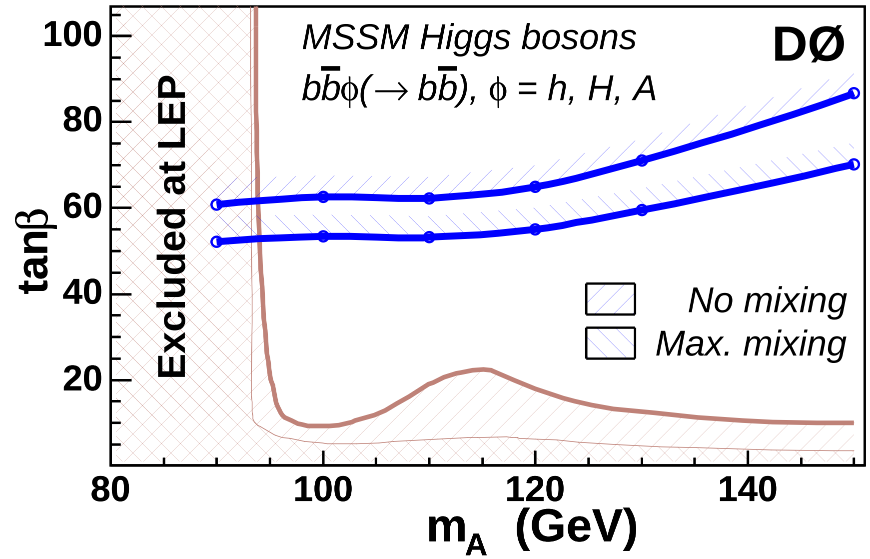
MSSM Higgs Boson Production at the Tevatron



- At large $\tan\beta$, Higgs production with bottom quarks becomes extremely important!

In Search Of...

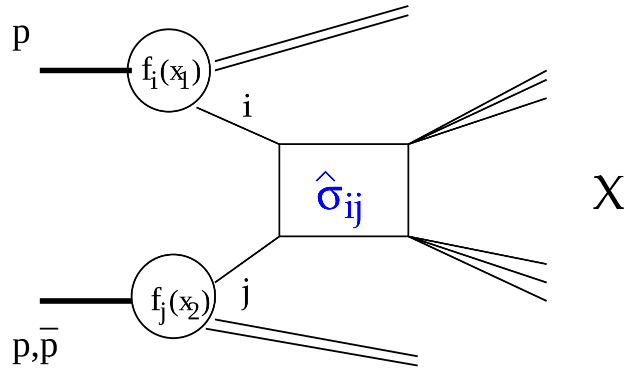




(from DØ Collaboration, hep-ex/0504018)

- Search for $h = h^0, H^0, A^0$ in 3 b-tagged events using DØ Run II data
- Significant portion of MSSM parameter space excluded ($\tan\beta \sim 50$)

Calculation of $p\bar{p}, pp \to Q\bar{Q}h$



- Hadronic cross sections can be factorized to separate the short distance effects (perturbative) from the long distance effects (non-perturbative) of the strong interactions.

$$\sigma(pp, p\bar{p} \to X) = \sum_{ij} \int dx_1 dx_2 f_i{}^p(x_1) f_j{}^{p,\bar{p}}(x_2) \hat{\sigma}(ij \to X)$$

$ij \to$ quarks or gluons

$f_i^p(x)$, $f_i^{p,\bar{p}}(x) \to$ Parton Distributions Functions

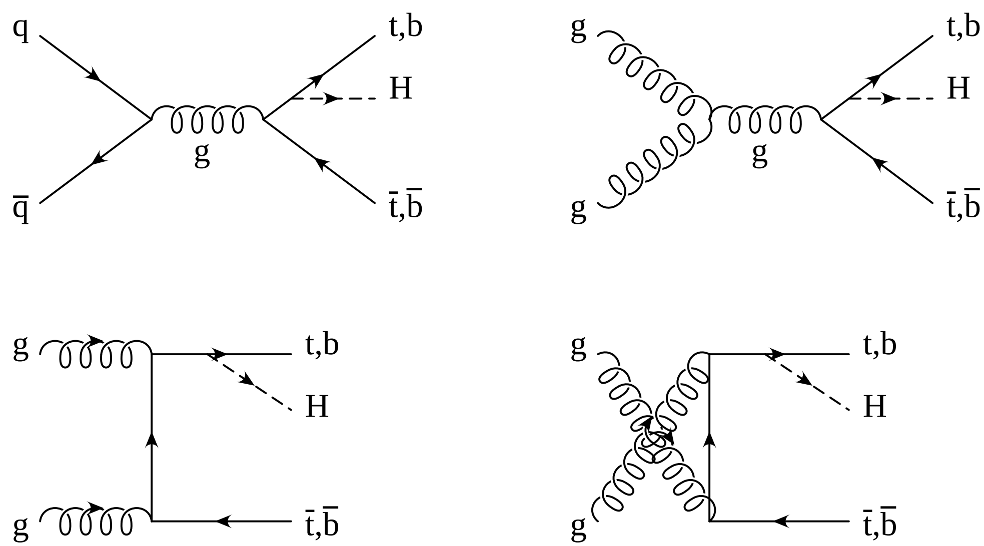
Perturbative Approach and scale dependence

- Since $\alpha_s(Q^2) \to 0$ for large Q^2, we can calculate $\hat{\sigma}(ij \to X)$ perturbatively $\longrightarrow$ QCD (Quantum Chromodynamics)
- At each order in α_s the expression of $\hat{\sigma}(ij \to X)$ contains infinities that are systematically canceled by a subtraction procedure: renormalization
- A remnant of the subtraction point is left over at each perturbative order as a renormalization scale dependence (μ_R):

$$\hat{\sigma}(ij \to X) = \alpha_s^k(\mu_R) \sum_{m=0}^{n} \hat{\sigma}_{ij}^{(m)}(\mu_R, Q^2)\alpha_s^m(\mu_R)$$

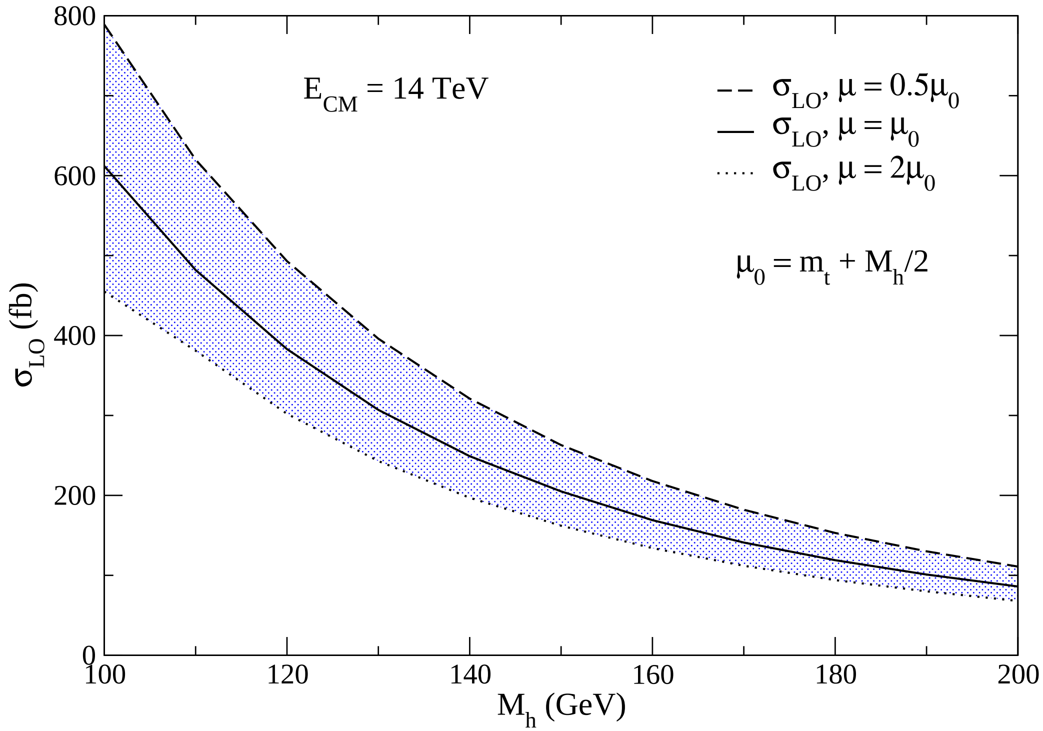
- Factorization also introduces a subtraction point dependence in the initial state parton densities: factorization scale dependence (μ_F)
- Theoretical error systematically organized as an expansion in α_s

SM Higgs Production with Heavy Quarks



- At tree level, partonic processes $\Rightarrow$ $q\bar{q}, gg \rightarrow Q\bar{Q}h$
- For $t\bar{t}h$, $q\bar{q}$ (gg) dominates at the Tevatron (LHC)
- For $b\bar{b}h$, gg dominates at both colliders
- Need a precise prediction for total and differential cross sections...

LO Prediction for $pp \to t\bar{t}h$ at the LHC



- LO cross section too unstable $\longrightarrow$ Need higher-order corrections!

NLO Calculation of $q\bar{q}, gg \to Q\bar{Q}h$

- NLO parton level cross sections:

$$\hat{\sigma}_{ij}^{NLO} = \hat{\sigma}_{ij}^{LO} + \frac{\alpha_s}{4\pi}\delta\hat{\sigma}_{ij}^{NLO}$$

NLO corrections made of:

$$\delta\hat{\sigma}_{ij}^{NLO} = \hat{\sigma}_{virt}^{ij} + \hat{\sigma}_{real}^{ij}$$

- Specifically: $\hat{\sigma}_{virt}^{ij} \to$ self-energy, vertex, box and pentagon loops and $\hat{\sigma}_{real}^{ij} \to$ real one gluon/quark emission
- Procedure:
  - Renormalize UV divergences
  - Cancel IR divergences in $\hat{\sigma}_{virt}^{ij} + \hat{\sigma}_{real}^{ij}$
  - Check μ-dependence of σ^{NLO}

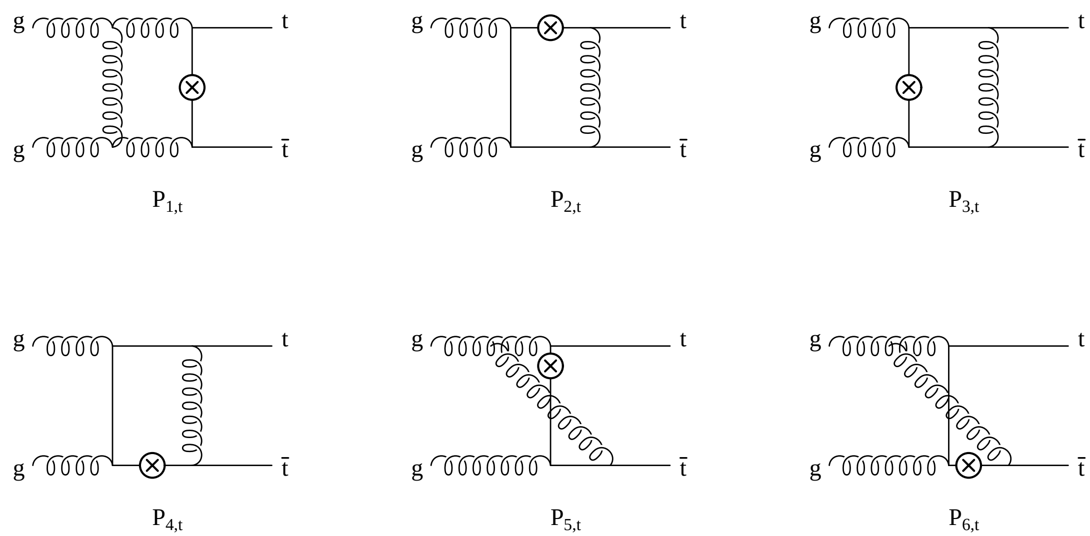
Calculation of σ_{virt}

- Amplitudes of diagrams calculated as a linear combination of Dirac structures with coefficients that depend on tensor and scalar one-loop Feynman integrals.
- Tensor integrals of the form:

$$\int \frac{k^\mu, k^\mu k^\nu, \cdots}{N_1 N_2 \cdots}$$

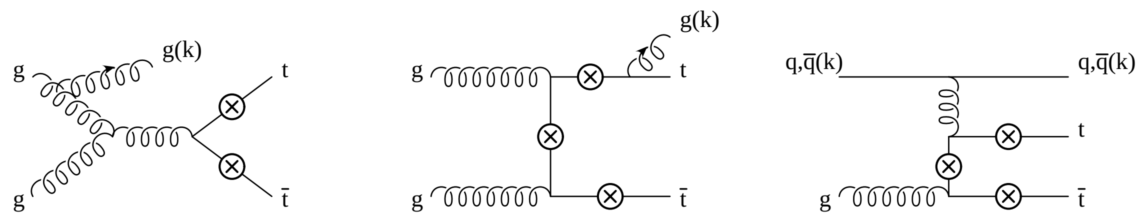
  are reduced to linear combinations of scalar integrals.
- Self-energy and vertex virtual diagrams give rise to UV divergences which are canceled by including suitable counterterms.
- IR divergences are also present in Vertex, Box and Pentagon diagrams (and some CT's). These divergences cancel against corresponding ones appearing in σ_{real}.

The Dreaded Pentagons!



- Pentagons contain both analytic and numerical "difficulties."
- Analytic $\Rightarrow$ calculation of scalar Feynman integrals with several internal/external massive particles (Done here for the first time!).
- Numerical $\Rightarrow$ tensor coefficients depend inversely on higher-powers of the Gram determinant ($\text{GD} = \det(p_i \cdot p_j)$). At the boundary of phase space GD $\rightarrow 0$.

Calculation of σ_{real}



- Real corrections contain IR divergences which can be either *soft* $(E_g \to 0)$ or *collinear* when the emitted parton is collinear with another massless parton.
- IR divergences cancel analogous divergences from σ_{virt}.
- Any left-over poles are canceled by counterterms of the PDFs.
- We have calculated σ_{real} using two different implementations of the Phase Space Slicing (PSS) method: the one- and two-cutoff methods (First time with several massive particles in final state!).

Idea of Phase Space Slicing

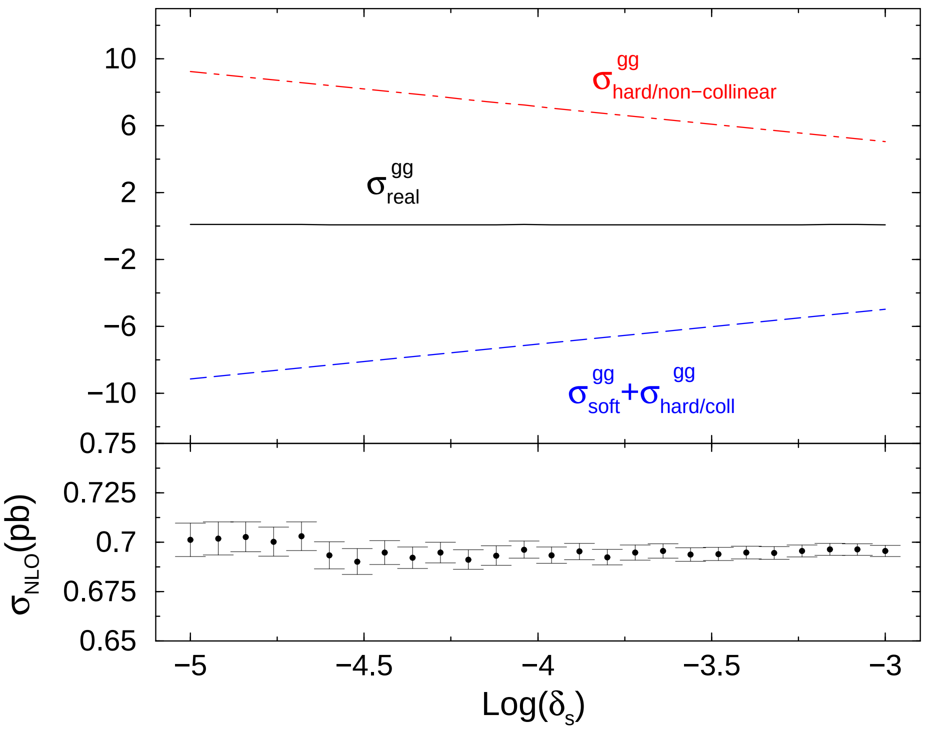
- Introduce cutoffs in the phase-space integration to isolate IR divergences:

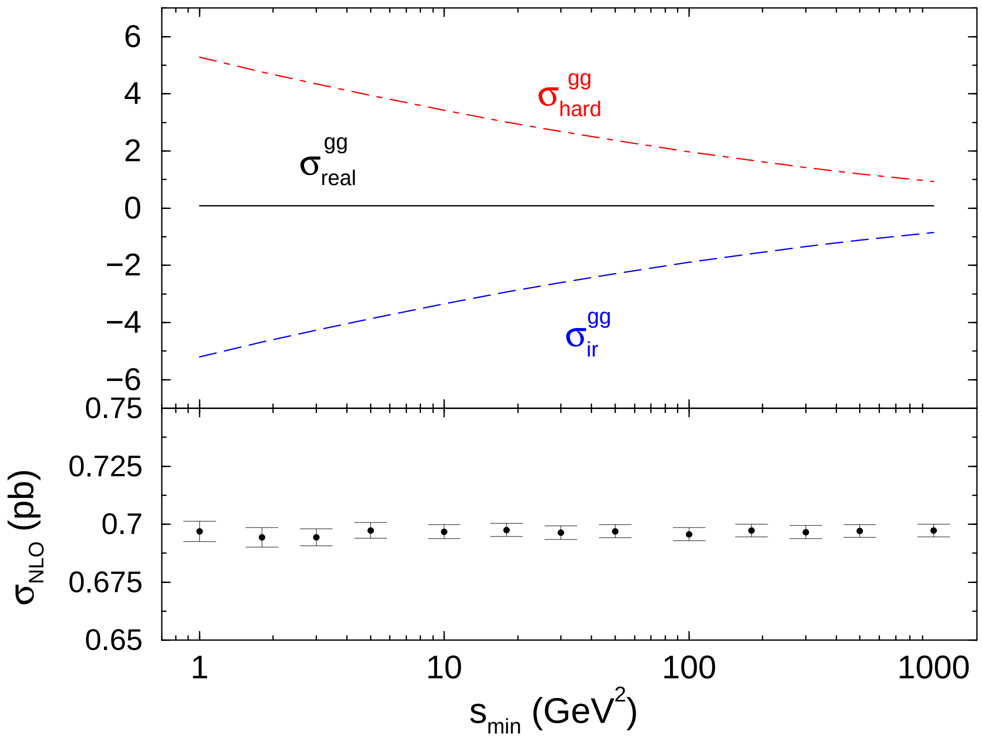
  - Two-cutoff method:
    $\sigma_{real} \stackrel{\delta_s}{=} \sigma_{soft} + \sigma_{hard} \stackrel{\delta_c}{=} \sigma_{soft} + \sigma_{hard,coll} + \sigma_{hard,non-coll}$

  - One-cutoff method:
    $\sigma_{real} \stackrel{s_{min}}{=} \sigma_{ir} + \sigma_{hard}$

- σ_{soft} and $\sigma_{hard,coll}$ (σ_{ir}) are (is) calculated analytically to extract *soft* and *collinear* singularities
- $\sigma_{hard,non-coll}$ (σ_{hard}) is calculated numerically (using MC techniques)
- End result: σ_{real} should be independent of the PSS cutoff(s).

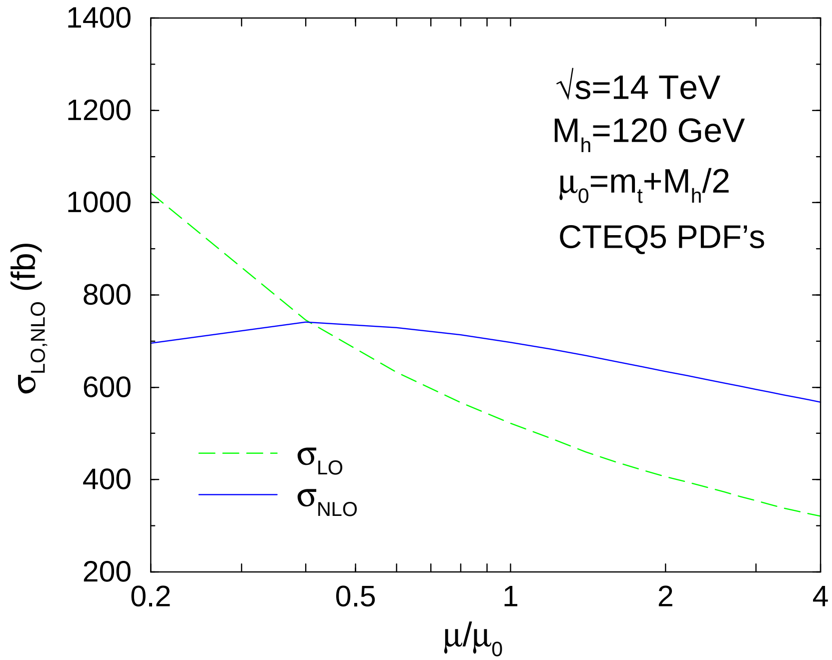
PSS Cutoff Independence

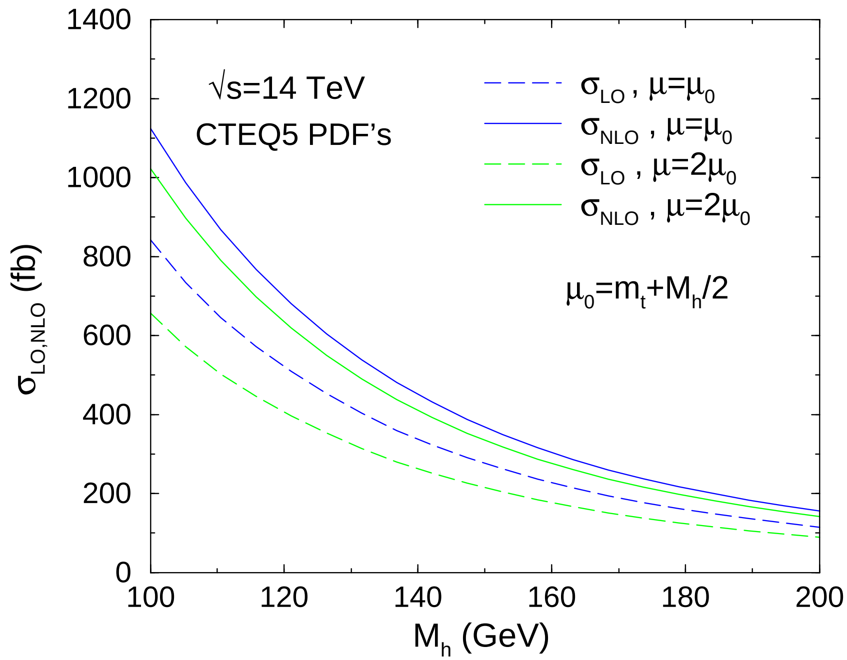




- Agreement between two approaches provides nice check on calculation

Total NLO Cross Section for $pp \to t\bar{t}h$ at the LHC





- Drastically reduced scale dependence
- NLO corrections increases LO cross section
- Beenakker et al (PRL 87 (2001) 201805) and S. Dawson, C.J., L. Orr, L. Reina and D. Wackeroth (PRD 68 (2003) 034022)

Critical Acclaim for Our Calculation

From "Higgs Physics at Future Colliders: recent theoretical developments", A. Djouadi —
"The cross section is rather involved at tree level since it is a three-body process, and the calculation of the NLO corrections was a real challenge...This challenge was taken up by two groups (of U.S. Ladies (31) and DESY gentlemen...)"

$\Downarrow$

References

(31) S. Dawson, C.B. Jackson, L. Orr, L. Reina and D. Wackeroth, Phys.Rev. D...

MSSM Higgs Production with Bottom Quarks

No Such Thing as a Free Lunch...

- Ideally, NLO calculation of $b\bar{b}h$ would follow from $t\bar{t}h$ with $m_t \leftrightarrow m_b$. BUT, there are some complications:
- Experimentally: since b quarks can be tagged, Higgs production with b quarks can be detected via:
  - Fully exclusive mode $\longrightarrow$ both b quarks are observed
  - Fully inclusive mode $\longrightarrow$ no b quarks are observed
  - Semi-inclusive mode $\longrightarrow$ at least one b quark is observed
- Theoretically: when a b quark is treated inclusively, the integration over its phase space gives rise to collinear logarithms:

$$\Lambda_b = \log\left(\frac{\mu_h^2}{m_b^2}\right)$$

- Perturbative expansion: $\alpha_s \to \alpha_s \Lambda_b$

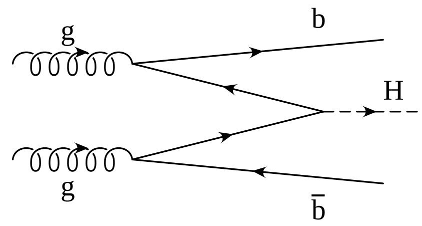
Two Calculational Schemes

- Four Flavor Number Scheme:
  - No special treatment of collinear logarithms
  - Full fixed-order calculation including Λ_b's and everything else.
- Five Flavor Number Scheme:
  - Assume (at LO) all b quarks are at low $p_T \rightarrow$ Only important contribution comes from the Λ_b's!
  - Factorize and resum Λ_b's by introducing a b PDF:

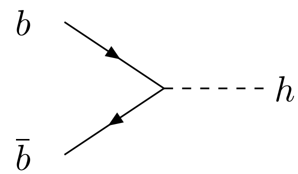
$$b(x,\mu) = \frac{\alpha_s(\mu)}{2\pi}\Lambda_b \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) g(y,\mu)$$

LO Processes in the 4FNS and the 5FNS

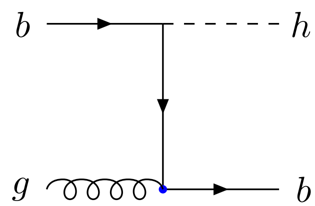
- 4FNS (all final states):

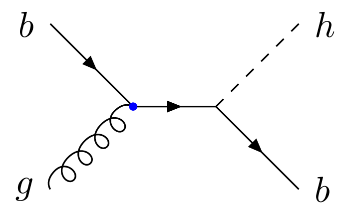


- Fully Inclusive 5FNS:



- Semi-inclusive 5FNS:



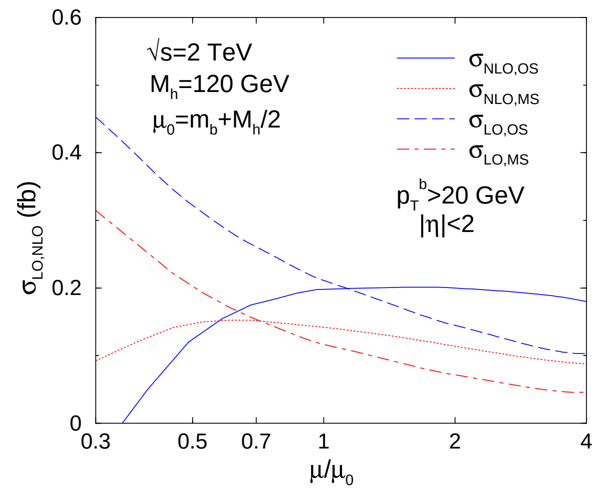


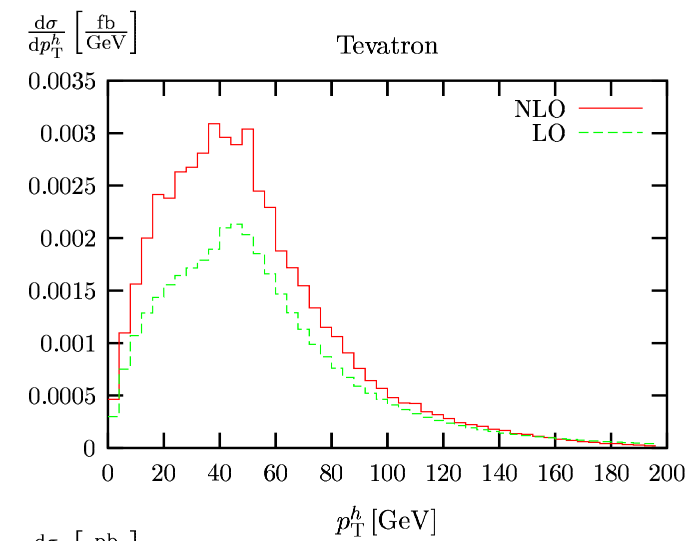
- $b\bar{b} \to h$ known at NNLO in QCD (Harlander and Kilgore) while $gb \to bh$ calculated at NLO (J. Campbell et al.)
- Important to study compatibility/validity of the 4FNS and 5FNS

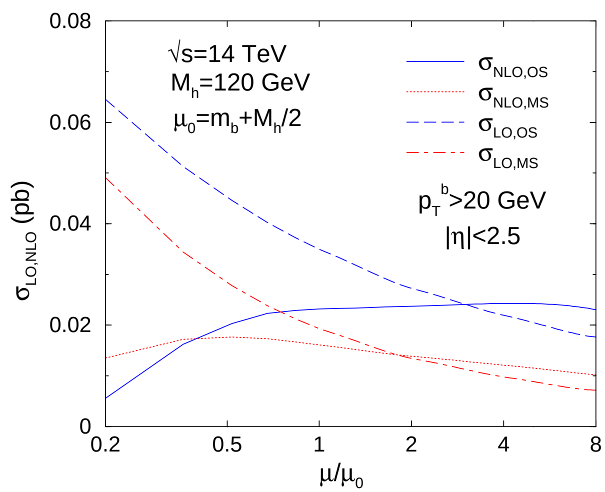
Fully Exclusive $b\bar{b}h$ Production

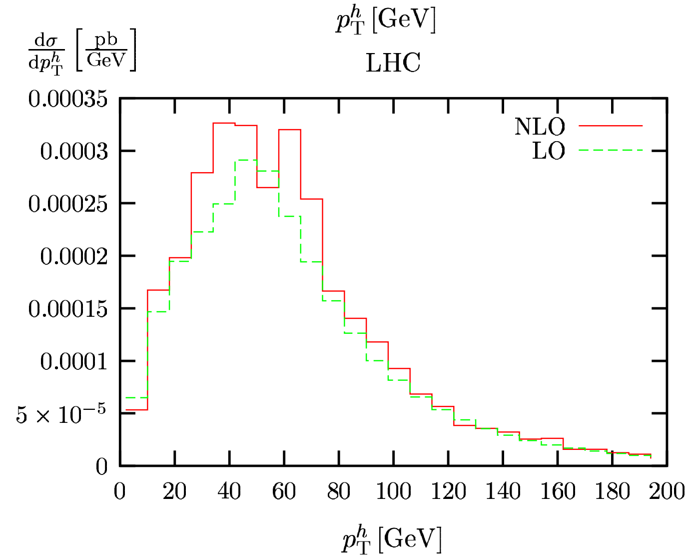
- Two independent calculations of NLO QCD corrections:
  - S. Dittmaier, M. Kramer, M. Spira (PRD 70 074010 (2004))
  - S. Dawson, C.J., L. Reina, D. Wackeroth (PRD 69 074027 (2004))
- Setup:
  - Require two high-p_T b jets in final state: $p_T^{b,\bar{b}} > 20$ GeV and $|\eta_{b,\bar{b}}| < 2(2.5)$ Tevatron (LHC)
  - Radiated g and $b/\bar{b}$ distinct only if $\Delta R > 0.4$
- Cuts reduce signal and background
- Renormalization/factorization scale dependence reduced
- Renormalization scheme dependence for m_b: OS vs.$\overline{MS}$

Results for Exclusive $b\bar{b}h$ Production

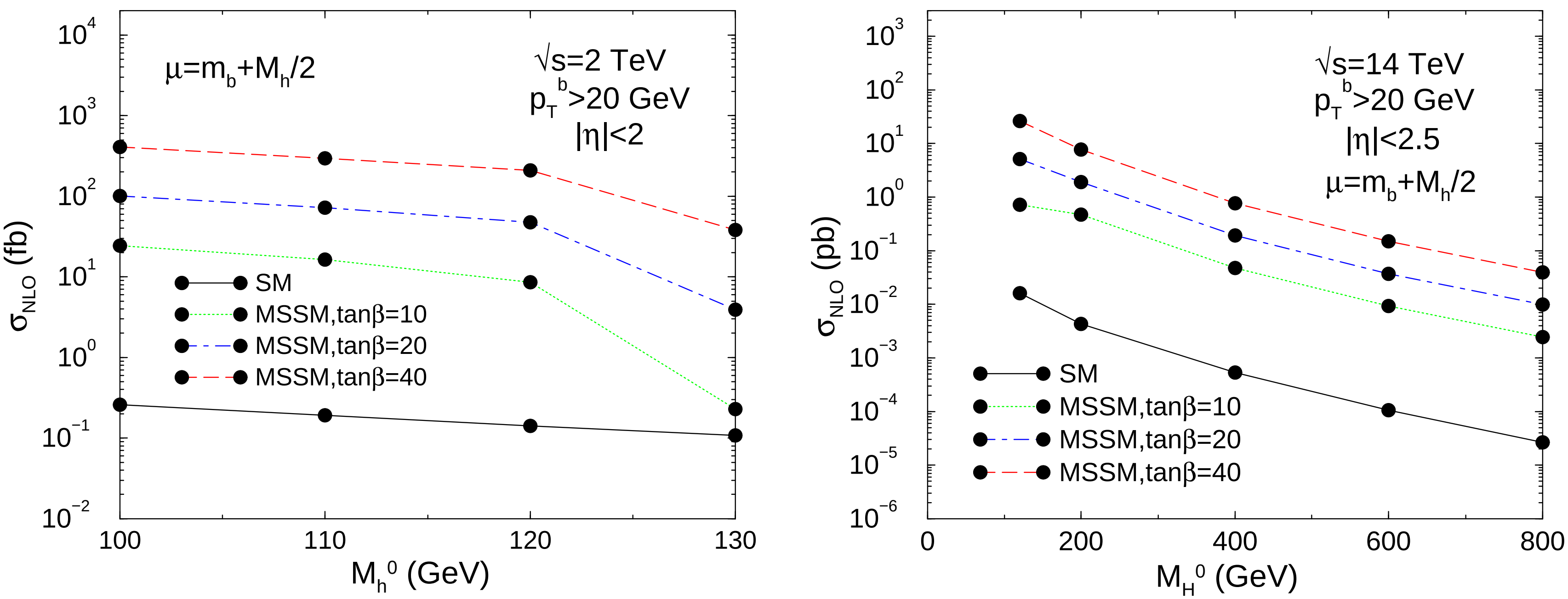








$M_H, \tan\beta$ Dependence for Exclusive $b\bar{b}(h^0, H^0)$

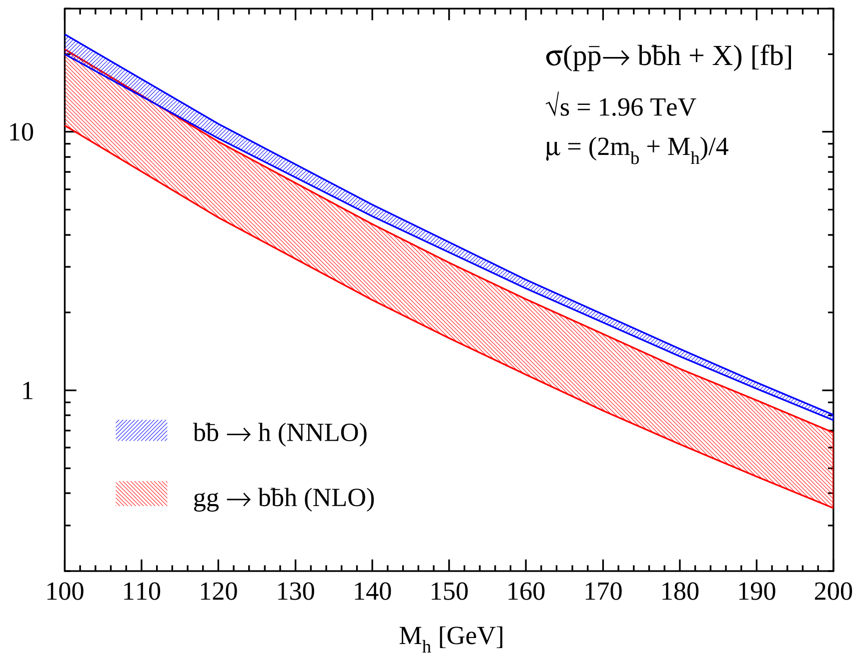


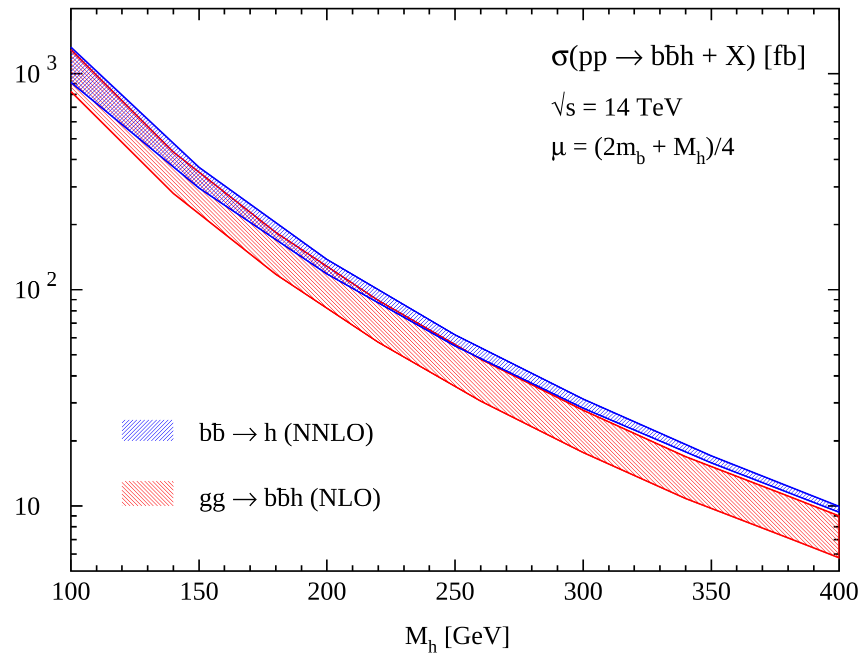
- Rescaling $\sigma_{SM} \rightarrow \sigma_{MSSM}$:

$$\sigma_{MSSM} = \left(\frac{g_{bbh}^{MSSM}}{g_{bbh}^{SM}}\right)^2 \left(\sigma_{SM} - \sigma_{SM}^t\right) + \left(\frac{g_{tth}^{MSSM}\, g_{bbh}^{MSSM}}{g_{tth}^{SM}\, g_{bbh}^{SM}}\right) \sigma_{SM}^t$$

Results for Inclusive $(b\bar{b})h$ Production

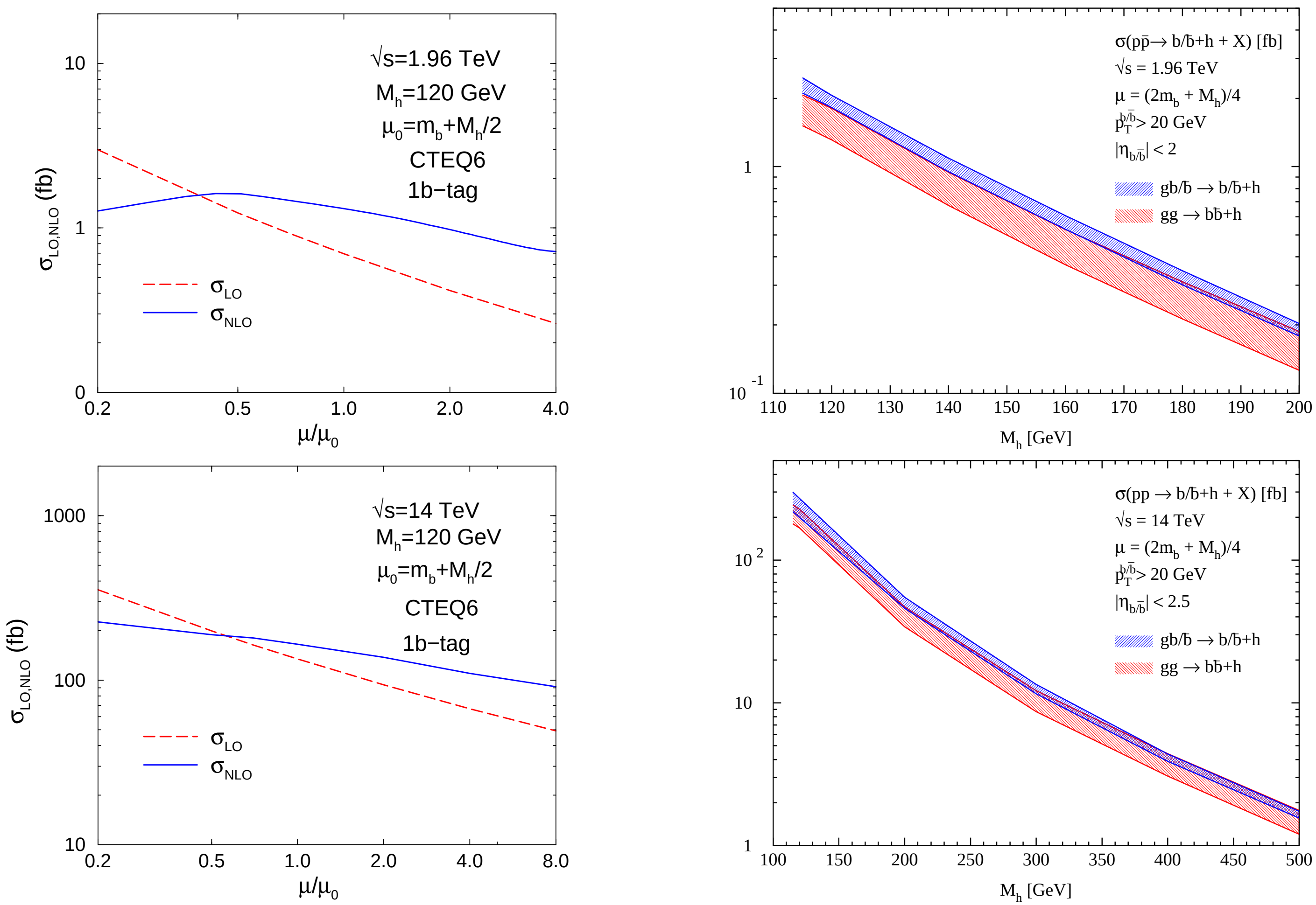
(from J. Campbell et. al. (Higgs Working Group), Les Houches workshop on Physics at TeV Colliders (2004), hep-ph/0405302)





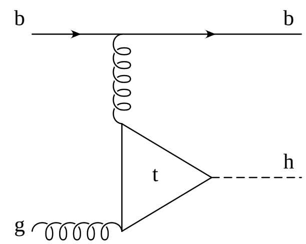
Results for Semi-Inclusive $b(\bar{b})h + (b)\bar{b}h$ Production

(from J. Campbell et. al. (Higgs Working Group), hep-ph/0405302)



Not the End of the Story...

- Diagrams containing loops of top (bottom) quarks neglected in 5FNS calculation of SM (MSSM) cross section

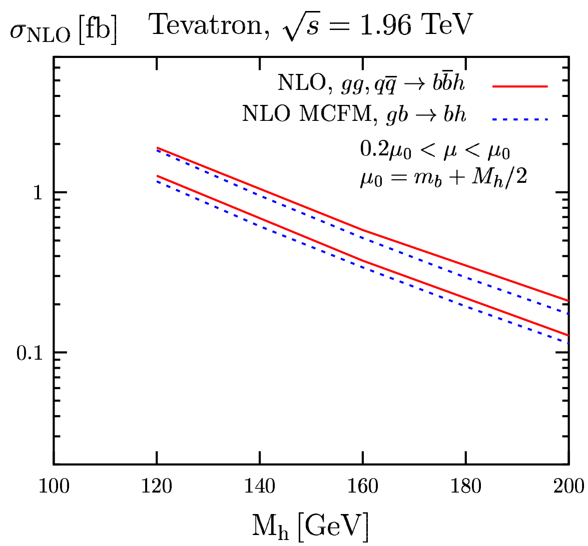


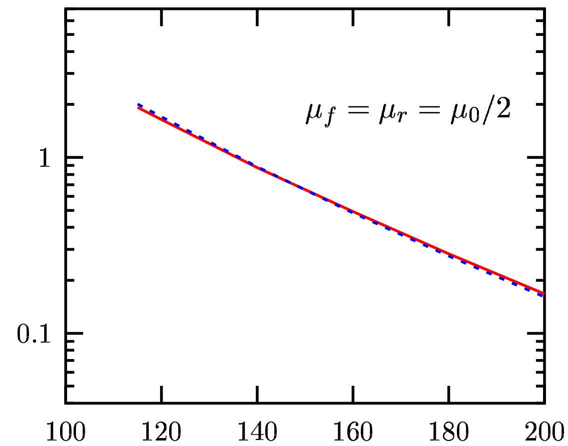
- $bg \to bh$ @ NLO performed in the $m_b = 0$ approximation:
  - Top (bottom) loop diagrams neglected since $\sigma_\Delta \propto m_b$
  - In SM, $\sigma_\Delta \sim \mathcal{O}(g_{hbb} g_{htt} \frac{m_b}{m_t}) \sim \mathcal{O}(g_{hbb}^2) \to$ could be numerically important!

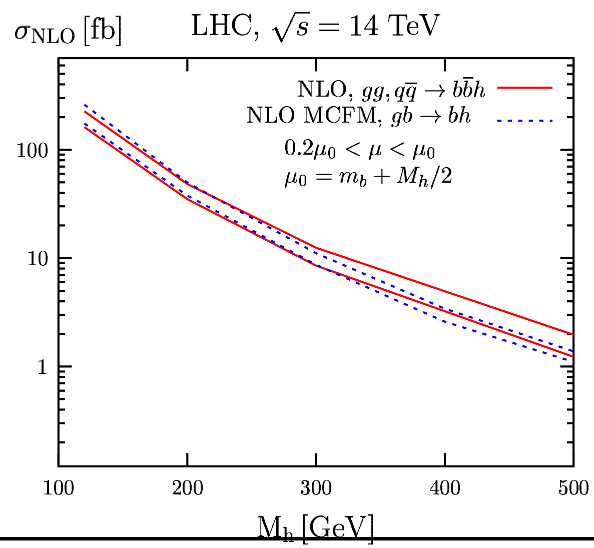
- To compare 4FNS and 5FNS for bh production, we coded σ_Δ into MCFM (Campbell and Ellis, webpage:mcfm.fnal.gov)

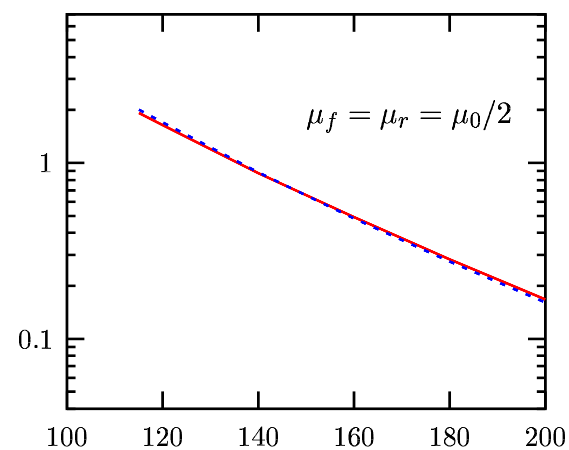
- Including top loop lowers $\sigma_{gb \to bh}$ by 15%(10%) at the Tevatron (LHC)

Results for Semi-inclusive Production...again









PDF Uncertainties

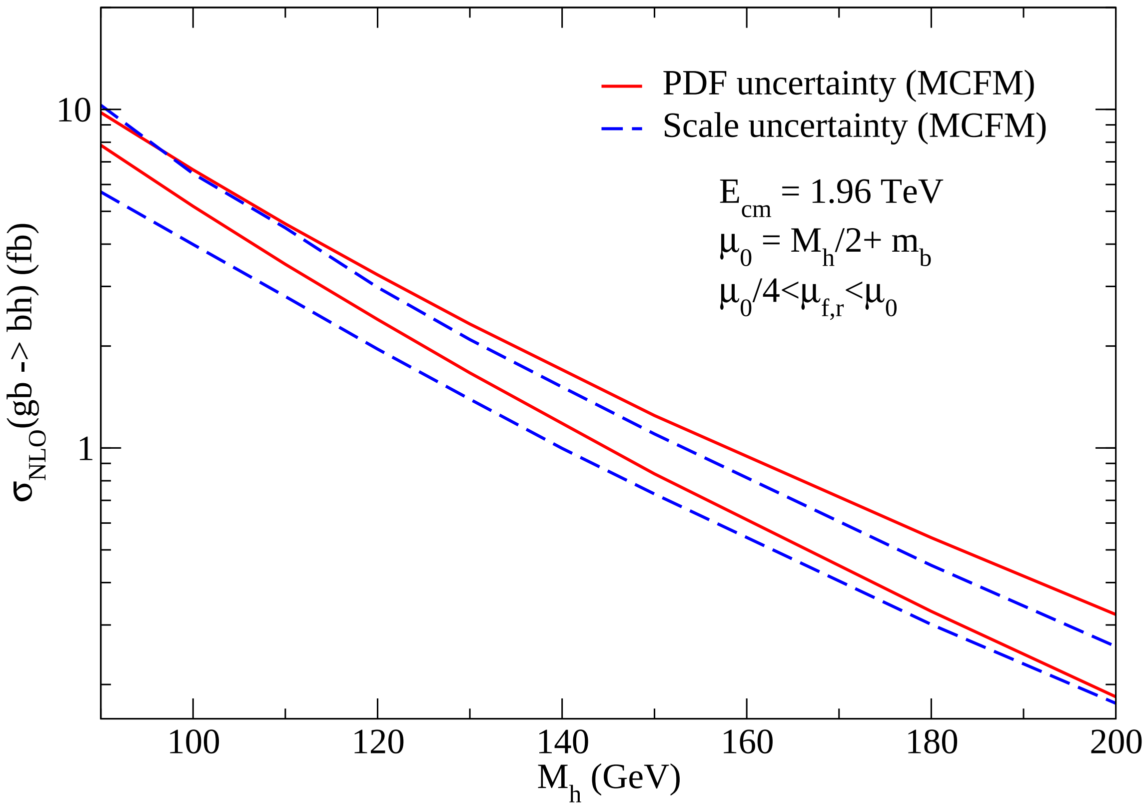
- Nominal set of PDFs (e.g. CTEQ6) obtained by fitting data from low-energy experiments to non-perturbative core equation (20 parameters)

- 20 parameters varied (in a well-defined manner) to *map* out neighborhood around the nominal fit $\longrightarrow$ 40 additional PDF sets

- Uncertainties (from PDFs) of observables $\rightarrow \Delta\sigma^{\pm} = \sqrt{\sum_i (\sigma_i - \sigma_0)^2}$

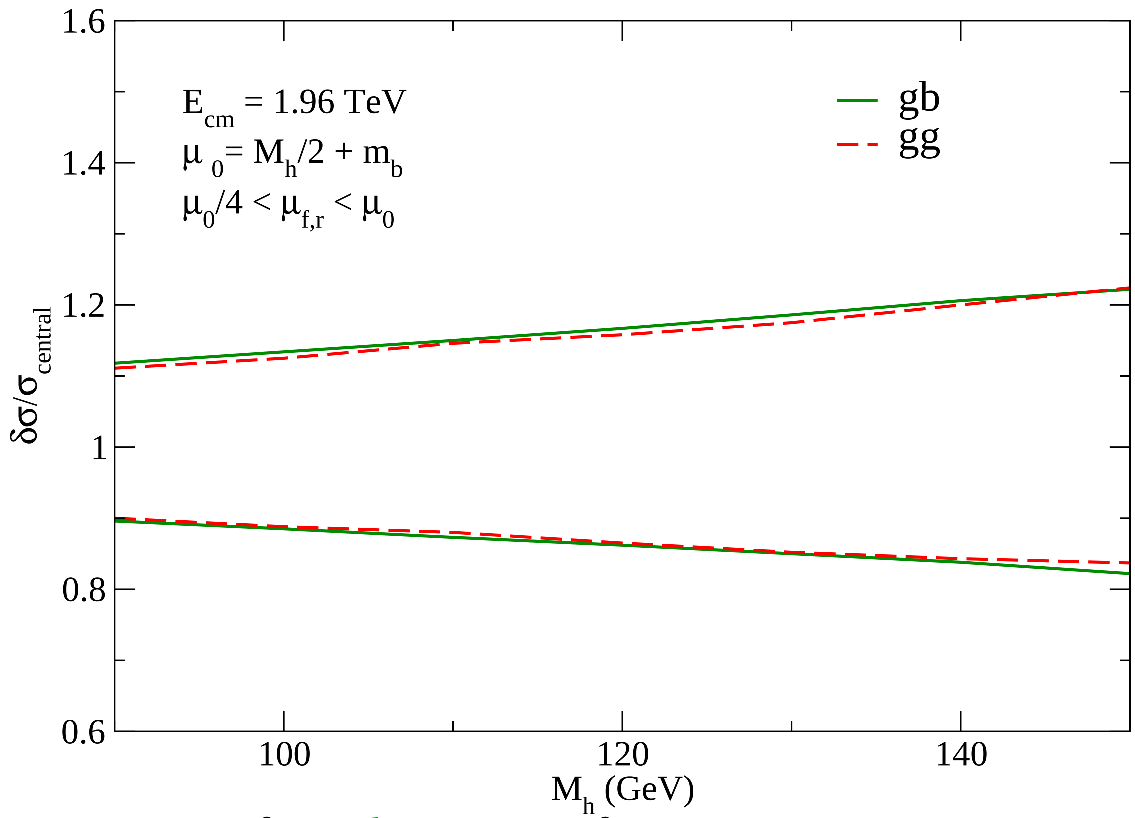
- Heavy quark PDFs not fit to data! Calculated perturbatively from gluon PDF $\Rightarrow$ b quark PDF uncertainties intimately related to gluon PDF uncertainties.

PDF Uncertainties for $gb \to bh$ at the Tevatron



- PDF uncertainties comparable to scale dependence uncertainties

PDF Uncertainties: 4FNS vs. 5FNS



- PDF uncertainties for *gb* $\simeq$ ones from *gg*

Summary

- "The Truth is Out There": experiments and theoretical arguments seem to be pointing to a light Higgs boson

- SM Higgs production with top quarks will play a crucial role at the LHC (for $M_h < 130 - 140$ GeV). $t\bar{t}h$ will also provide the only direct measurement of the top quark Yukawa coupling.

- We have performed the NLO QCD calculation of $t\bar{t}h$ production:
  - The NLO cross section exhibits a drastically reduced dependence on renormalization/factorization scales ($\simeq 15 - 20\%$).
  - NLO corrections increase the LO cross section over the full M_h range considered.

Summary (cont.)

- MSSM Higgs boson production with bottom quarks could be the first signal of new physics at the Tevatron. We have calculated the NLO QCD-corrected cross section for $b\bar{b}h$ production for all three final states:
  - Fully exclusive prediction exhibits significantly reduced dependence on the μ_r/μ_f scales ($\simeq 15\%$). Renormalization scheme dependence from $m_b(\mu_R) < 15-20\%$.
  - 4FNS/5FNS predictions for fully inclusive and the semi-inclusive modes now agree within theoretical uncertainties. The agreement between the two schemes is greatly improved by including top-quark loops previously neglected in the 5FNS.
  - PDF uncertainties $\simeq 10-30\%$ range at the Tevatron.